

Title: Covert Contrast and Covert Error in Persistent Velar Fronting

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Abstract

Acoustic and articulatory studies demonstrate covert contrast in perceptually neutralised phonemic contrasts in both typical children and children with speech disorders. These covert contrasts are thought to be relatively common and symptomatic of phonetic speech disorders. However, clinicians in the speech therapy clinic have had no easy way of identifying this covertness. This study uses ultrasound tongue imaging to compare tongue contours for /t/ and /k/ in seven children with persistent velar fronting. We present a method of overlaying tongue contours to identify covert contrast at the articulatory level. Results show that all seven children, contrary to expectations, produced both /t/ and /k/ with near-identical tongue shapes showing no evidence of covert contrast. However, further analysis of one of the participants showed highly variable tongue shapes for /t/ and /k/, including retroflex productions of both. Although not phonologically conditioned, this covert error is evidence of speech disorder at the phonetic level.

Keywords

Covert Contrast, Covert Error, Ultrasound, speech sound disorders, velar fronting

Introduction

During speech acquisition it is common for children to make apparent substitutions of one speech sound for another present in the target language. This collapse of category, or neutralisation, results in homophony where there ought not to be, and is taken to suggest that children have a difficulty at the phonological level. However, increasing evidence in the literature suggests that these contrasts are not always completely neutralised, but merely difficult to perceive by the adult listener who tends to categorise children's productions into their own phonological categories (Liberman, Harris, Hoffman, & Griffith, 1957). These covert contrasts might be a relatively common phenomenon in both typical children's speech acquisition and in children described as phonologically delayed/disordered. Munson, Edwards, Schellinger, Beckman, and Meyer (2010, p248) go as far as to say that covert contrast "might be the rule, rather than the exception" with strong evidence that the broad phonetic transcriptions carried out by clinicians mask the subtle phonetic difference between phonemes transcribed and analysed as neutralised.

Covert contrast may in fact reveal a pervasive effect of overly-broad transcription (Oller & Eilers, 1975) in the clinic driven by either expectation or a focus on quick and subjective binary correct/incorrect judgements for scoring purposes. However, the real theoretical importance lies first in whether the typical, delayed and disordered development of children's speech involves clear categorical phonological substitutions at an abstract representational level preceding planning or not (Scobbie, Gibbon, Hardcastle & Fletcher, 2000). Alternatively, phonological distinctiveness could be compromised but not wholly neutralised, or clearly distinct mental representations might be phonetically planned or executed in such a way that the phonologically distinct speech events which are produced cannot be (easily) distinguished by a listener. Locating a disorder at the right place in the speech production chain is important for diagnosis and treatment.

Traditionally, evidence for covert contrast comes from acoustic studies of contrasts which appear neutralised. For example Maxwell and Weismer (1982) detected difference in the voice onset time for voiced and voiceless stops in a boy aged 3;11 with a severe "articulation disorder" (note

that in the 1980s this term was common place for a variety of speech sound disorders) and no overt voicing distinction. Similarly, other studies have found differences at the acoustic level for place of articulation (e.g. Forrest, Weismer, Hodge, Dinnsen, and Elbert, 1990). When evidence is found for covert contrast, the implication is that the child has separate phonological representations for each of the phonemes in question, rather than a collapse of categories. The child's speech sound disorder is therefore at the phonetic or articulatory level (Gibbon, 1999). This, then, has clear implications for the type of intervention approach clinicians should select, and yet the research on covert contrast has had little impact on the decisions made in the speech therapy clinic (Munson et al., 2010). This must in part be because, by very definition, covert contrast is difficult for the clinician to identify and while acoustic analysis methods are reported in the literature, there is no software package available for clinicians to use to automatically identify covert contrasts in the acoustic signal because phonemes do not have a single easily identifiable acoustic correlate (Munson et al., 2010).

In contrast to acoustic methods of identifying covert contrast, a smaller number of studies have used instrumental articulatory methods. This is appealing for two reasons. Firstly, children may mark contrasts in unusual and unexpected ways making it impossible to predict which acoustic measure will be useful, and secondly often the instrumental technique in question is an obvious choice for remediating the child's apparent neutralisation. For example, Gibbon (1990) used electropalatography (EPG) to investigate articulation problems in a four year old, "MB", with alveolar backing. Results showed, in fact, a covert contrast in the timing of alveolar and velar gestures, with a difficulty controlling the precise timing required for the release of an alveolar stop, resulting in the percept of [g] for /d/ and suggesting a motor control difficulty. While Gibbon suggests several options for the remediation of MB's speech disorder, she goes on to suggest that EPG might be an appropriate therapy technique. Children with motor control difficulties, such as those described here, need therapies which capitalise on the principles of motor learning. It is on these principles that visual biofeedback methods such as EPG and ultrasound visual biofeedback are founded.

Therefore, where a covert difference in tongue shape or position is detected this can be remediated using a technique that aims to change these very dimensions.

Covert Error

In addition to covert contrast, but equally important for addressing the precise phonological or phonetic nature of a disorder, a number of speech errors which defy broad phonetic transcription have also been reported in the literature, again, mainly in EPG studies. Gibbon (1990) has been influential in her description of “undifferentiated lingual gestures” where the EPG patterns of “phonologically disordered” children reveal difficulty differentiating coronal and dorsal tongue gestures, again pointing towards an issue with the precise motor control required for intelligible speech. A number of other types of errors revealed by EPG are reviewed by Hardcastle and Gibbon (2005), including misdirected articulatory gestures and double articulations where they ought not to exist. While these covert errors may not be contrastive, they are nonetheless important diagnostically because again they provide evidence for motoric difficulties, perhaps suggesting different therapy approaches might be required.

Ultrasound tongue imaging.

Ultrasound tongue imaging (UTI) is a relatively new tool to clinical phonetics, with as far as we are aware only one recent study using it to identify covert contrast (McAllister-Byun, Buchwald & Mizoguchi, 2015) and a different study by Bressmann, Radovanovic, Kulkarni, Klaiman, and Fisher (2011) using the technique to show covert articulatory movements in speakers with cleft palate. UTI uses standard medical ultrasound to image the tongue in real-time making it suitable for visual biofeedback therapy, with over 20 small studies showing it to be effective for treating persistent speech sound disorders (see for example, Cleland, Scobbie & Wrench, 2015) and other studies using it for fine articulatory analysis of lingual movements when synchronised to the acoustic signal (for example, Heyde, Scobbie, Lickley, and Drake, 2015). The probe is placed under the chin, capturing

most of the surface of the tongue in either the mid-sagittal or coronal plane. In both views, the imageable area is constrained by shadows from bone, with the tongue tip in particular being susceptible to a shadow from the mandible. Unlike EPG, the speaker is not required to have any custom-made appliances and as such it is potentially a quicker and easier way to identify covert contrast (McAllister Byun et al., 2015) which might translate to the clinic if simple analysis methods can be found. The purpose of this study was therefore to contribute one such analysis method so that ultrasound can be used for diagnosis of specific types of speech disorders (Bressmann et al., 2011) and remediation of the same errors (Cleland et al., 2015).

Velar Fronting

Velar fronting is a well attested phonological process in both the speech of young typically developing children and older children with speech sound disorders, with typically developing children acquiring velars by the time they are three and half years old (Dodd, 2013). In a minority of children, velars pose a particular difficulty, despite phonological therapy. These, older, children fail to differentiate coronal (tongue tip) and dorsal (tongue body/back) articulations and thus may present with motoric deficits (Gibbon, 1999) or a phonetic explanation for velar fronting. Velars and alveolar are an appropriate choice for testing the utility of UTI as a tool for identifying covert contrast as, using the mid-sagittal view, the front and the back/root of the tongue are clearly visible and overt contrasts in k/t are easily identified (see Cleland et al., 2015). Moreover, Ultrasound can be used as a tool for remediating persistent velar fronting (Cleland et al., 2015). Figure 1 shows a typical UTI taken at the burst of [t] and [k] in a typically developing child, with the tongue-tip to the right. Since the hard palate is not imaged with ultrasound, it is not possible to determine from these images alone that alveolar closure has been achieved. It is, however, possible to see contact between the back of the tongue and the velum in some speakers, indicating velar closure. Tongue shapes for [k] are characterised by a raised tongue dorsum (a “domed shape”) and [t] tongue shapes are characterised by a raised tongue tip and usually flat tongue body.

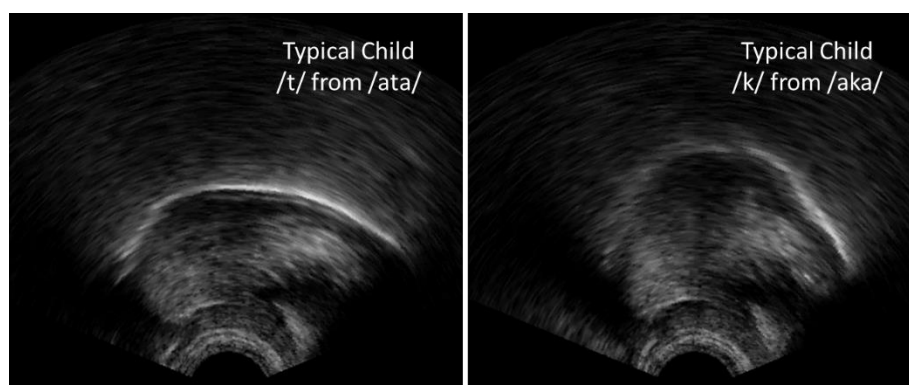


Figure 1: Typical ultrasound images for /t/ (left) and /k/ (right). Tongue tip to the right.

A recent study has already used UTI to investigate covert contrast in velar fronting. McAllister Byun and colleagues (2015) used both acoustic analysis and the Dorsum Excursion Index (DEI, Zharkova, 2013), a measure of dorsal raising essentially, to determine whether differences could be found between /t/ and /k/ targets in two children presenting with velar fronting and two children who had already developed the contrast. Results showed that for one participant, Rory, the DEI was unable to detect a covert contrast in t/k. However, for the other child, Max, with positional velar fronting there was a significant effect of vowel context, with velar targets produced with higher DEI in front vowel contexts, providing promising evidence for covert contrast. This study, however, was limited to a statistical comparison of measures extracted from the ultrasound, rather than a direct comparison of tongue shapes. Whilst useful for answering theoretical questions, for clinicians the ability to compare two tongue shapes side by side (or by dynamically superimposing one on the other) might be more useful, with Klein, McAllister Byun, Davidson and Grigos (2013) advocating that trained clinicians are able to categorise ultrasound tongue shapes by visual gestalt, perhaps suggesting that access to the visual information provided by ultrasound is enough to enable clinicians to detect covert contrasts. However, if visual analysis is performed “live” or by looking at single still images side-by-side then it is possible that only large differences between tongue shapes would be detected, for example when the covert contrast is achieved in a very different manner (for example, retroflexion is very salient on ultrasound images). It is harder to imagine that visual inspection would

be adequate for detecting small changes in, for example, retraction of the tongue root. For this, overlaying of multiple ultrasound images and stabilisation of the probe becomes important.

In this study an objective method of analysing tongue shapes is adopted in preference to visual inspection in order to improve the likelihood of detecting covert contrast and covert errors. Using AAA software (Articulate Instruments, 2015) tongue surface splines are overlaid for visual comparison, as might be employed in the clinical context, and quantified by statistical analysis of radial differences in tongue shape to confirm or refute subjective impressions from visual inspection.

Purpose and hypotheses

The purpose of the current study was to determine whether articulatory evidence of covert contrast could be found in children with persistent velar fronting and to demonstrate a simple method of comparing tongue shapes that might be useable in the field in the future. We hypothesised that covert contrast would be indicated by a statistically significant difference in tongue shapes for /k/ and /t/ attempts despite perceptual neutralisation of these phonemes. In addition to covert contrast, we sought to determine whether children with persistent velar fronting display other imperceptible error types during attempts at /k/ and /t/, which although perhaps not contrastive, might also point towards a phonetic or motor basis as the cause of the speech disorder. This detailed phonetic analysis was carried out on one child with a history of severe SSD.

Method

Two studies were carried out. Firstly, a group study of velar fronting in seven children focusing on the shape and location of the midline tongue surface at the burst of /t/ and /k/ minimal pairs, and secondly a more exploratory case study of one of the children- 01F_Ultraphonix, or “Rachel”.

Study One: Group Study

Participants

Data comes from seven participants aged 6;0 to 10;11 with persistent primary SSDs and highly consistent velar fronting in all word positions from the perspective of transcription/percentage velars correct and their clinical referral. The children were participants in two different intervention studies: the Ultrax Project (<http://www.ultrax-speech.org/>) and the UltraPhonix project (<http://www.qmu.ac.uk/casl/ultraphonix/default.htm>). All the children went on to have ultrasound visual biofeedback therapy to establish correct [k] production. The results of the intervention for children in the Ultrax project are reported in Cleland, Scobbie, and Wrench (2015), intervention results for the remainder of the children are in preparation. For both studies children were recruited from local Speech and Language Therapists. We requested children aged over six with lingual errors which had been unresponsive to treatment. The children presented here are a subset of both projects who received treatment targeting production of velars. All participants were monolingual speakers of English and all had received speech therapy in the past, but not using any visual biofeedback methods. Children were selected if they had less than 20% velars correct at baseline probes (see below) and the data presented here were recorded before intervention commenced.

Participant details are reported in table 1, including each child's standardised score on the British Picture Vocabulary Scale (Dunn et al., 2009) and the subtype of Speech Sound Disorder which was diagnosed by the referring clinician in accordance with Dodd's subtypes (as is the case in the UK) of articulation disorder, phonological delay, inconsistent/consistent phonological disorder or developmental verbal dyspraxia (Dodd, 2013).

| Participant | Project | Age | Sex | BPVS | | SSD Subtype |
|-------------|-------------|------------|-----|--------------|--------------|------------------------------------|
| | | | | SS | DEAP PCC | |
| 01M | Ultrax | 6;0 | M | 109 | 75 | Consistent Phonological Disorder |
| 05M | Ultrax | 6;5 | M | 107 | 52 | Consistent Phonological Disorder |
| 06M | Ultrax | 6;0 | M | 80 | 58 | Phonological Delay |
| 07F | Ultrax | 7;6 | F | 109 | 86 | Phonological Delay |
| 01F | UltrapHoniX | 8;8 | F | 80 | 70 | Inconsistent Phonological Disorder |
| 03F | UltrapHoniX | 10;11 | F | 77 | 57 | Developmental Verbal Dyspraxia |
| 04M | UltrapHoniX | 7;2 | M | 108 | 72 | Phonological Delay |
| MEAN | | 7;6 | | 95.71 | 67.10 | |

Table 1: Participant details. BPVS: British Picture Vocabulary Scale- 3 standard score (Dunn et al., 2009); DEAP: Diagnostic Evaluation of Articulation and Phonology, (Dodd et al., 2002) Phonology subtest, percentage consonants correct, assessment recorded at second baseline, B2.

As part of both intervention studies children completed at least two baselines designed to probe accuracy of velar consonants and determine whether the children had any additional errors. At baseline 1 the participants completed the articulation and phonology subtests of the Diagnostic Evaluation of Articulation and Phonology (DEAP, Dodd, Hua, Crosbie, & Holm, 2002). All speech measures were recorded with simultaneous ultrasound (see below). In the DEAP articulation subtest 01M_Ultrax, 05M_Ultrax, 06M_Ultrax, 07F_Ultrax and 01F_UltraPhoniX were unable to imitate [k] in isolation. 04M_UltraPhoniX was able to achieve an acceptable [k] in isolation on three consecutive trials and 03F_UltraPhoniX was able to imitate 2/3 [k] in isolation. In addition the children completed the DEAP phonology subtest. Table one shows the group results for the measures, with numbers expressed as standard scores or percentages as appropriate. Table two shows an error analysis from the DEAP phonology subtest for each speaker, to allow the reader to gauge the severity of each child's speech sound disorder.

| PARTICIPANT | | | | | | | | | |
|----------------------------|-------|-------|-------|------|-------------|-------|-------|--------|---------------|
| Ultrax | | | | | Ultraphonix | | | | |
| PROCESS | 01M | 05M | 06M | 07F | 01F | 03F | 04M | Total | %Total Errors |
| Velar Fronting | 16 | 14 | 12 | 18 | 20 | 14 | 20 | 114 | 44.19 |
| Labialisation of sibilants | | | | | | 4 | | 4 | 1.55 |
| Post alveolar fronting | 2 | 5 | | | 5 | 1 | 6 | 19 | 7.36 |
| Backing | | | | | | 1 | | 1 | 0.39 |
| Gliding | 13 | 10 | 12 | | 8 | 7 | 14 | 64 | 24.81 |
| Stopping | | | 1 | | 1 | 5 | | 7 | 2.71 |
| Deaffrication | | 1 | | 1 | 1 | 3 | | 6 | 2.33 |
| Voicing errors | | 1 | 4 | | | 4 | | 9 | 3.49 |
| Weak syllable deletion | | 1 | 1 | | | | | 2 | 0.78 |
| FCD | | 1 | | | | 7 | | 8 | 3.10 |
| MCD | | 1 | | | 1 | 2 | | 4 | 1.55 |
| Cluster Reduction | | 7 | 9 | | 6 | 11 | | 33 | 12.79 |
| Other | | 7 | 2 | | | 2 | | 11 | 4.26 |
| TOTAL | 31 | 48 | 41 | 19 | 42 | 61 | 40 | 282 | 100 |
| % Total Errors | 12.02 | 18.60 | 15.89 | 7.36 | 16.28 | 23.64 | 15.50 | 109.30 | 100 |

Table 2: Phonetic and Phonological Analysis. FCD: Final consonant deletion; MCD: word medial consonant deletion.

All of the children also completed a wordlist designed to sample velar consonants in a variety of word positions and vowel environments, producing one token of each word. Wordlists differed between projects (the newer UltraPhonix wordlist is an enlargement of the Ultrax list with 105 rather than 64 words, more minimal pairs and more systematic sampling of vowel context) but are equivalent in that they sample word initial singleton t/k minimal pairs (or near minimal pairs) in a range of vowel contexts. These were:

Ultrax: tore/core, table/cable, tie/Kai, toot/coot (Kai is a common first name in the UK)

UltraPhonix: keep/team, cape/tape, Ken/ten, cab/tab, cop/top, core/tore, cool/tool, cub/tub, kip/tip, coy/toy.

Ultrasound Recording

The ultrasound system used was a high-speed cineloop system (Wrench and Scobbie, 2011) with audio synchronisation allowing us to accurately identify tongue shape within 10ms of the acoustic burst of /t/ and /k/, and which was probe-stabilised with a headset (Scobbie, Wrench and Van der Linden, 2006) to allow us to compare tongue shape for /t/ and /k/ directly. The headset was fitted in such a way that the mandible and hyoid shadows were symmetrical on the image, thus ensuring we could see as much of the tongue as possible. However, it should be noted that this approach is approximate and therefore rotation of the images differs between speakers. The headset can become heavy and uncomfortable over time and for this reason recordings were restricted to a maximum of 50mins and removed sooner at participant's request. The wordlists analysed here took around 10 to 12mins to elicit. All children tolerated the headset during the recording session without having to remove and refit it. Whilst the headset does restrict jaw movement somewhat, we ensured that all speakers were able to articulate the Scottish English corner vowels /i,a,o/ comfortably before beginning as part of our protocol for fitting the headset.

Ultrasound data was acquired using an Ultrasonix SonixRP machine remotely controlled via Ethernet from a PC running Articulate Assistant Advanced TM software (Articulate Instruments Ltd, 2012) versions 2.14 to 2.16 which internally synchronise the ultrasound and audio data. The echo return data was recorded at 121 frames per second (fps), i.e. 8ms per frame with a 135 degree field of view (FOV) in the mid-sagittal plane. Simultaneous acoustic and lip-camera recordings were also made, using an audio technica 803D clip-on microphone sampling at 22050Hz and a NTSC micro-camera (deinterlaced to 60fps), and synchronised to the audio with an electronic clapperboard (SyncBriteUp TM, Articulate Instruments Ltd, 2010).

Auditory Analysis

A broad phonetic transcription of the probe data (/t/ and /k/ segments only) was performed by the clinician using the acoustic data. Note, whilst this was somewhat broad, the clinician was

encouraged to use the full range of IPA and extIPA symbols rather than make a forced choice between /t/ and /k/. This allows us to determine whether there was indeed a perceptual neutralisation in the children's speech. It should be noted that this does not mean that no perceptual difference exists. Several studies (see for example Munson et al., 2010) have suggested that listeners are able to perceive gradient differences when perceptual rating scales are used. Rather, it suggests that at the level of transcription employed by most SLTs in the field, children would be judged to have neutralised the contrast. Two final year Speech and Language Therapy students who had completed their phonetics training provided inter-rater reliability for 25% of the data.

Ultrasound Analysis and Outcome Measures

Using AAA v2.16 software (Articulate Instruments, 2012) /t/ and /k/ segments were annotated at the beginning of the burst, the corresponding ultrasound frame was then selected and a spline indicating the tongue surface fitted to the image using the semi-automatic edge-detection function in AAA software. This choice of a temporal alignment is most appropriate for an association of tongue shape to burst acoustics and provides a consistent anchor point. Our choice of burst is pragmatic in nature since it is difficult to identify the entire closure phase, as is the tradition in EPG research, with ultrasound alone. The data analyst draws a spline in the region of the ultrasound image of the tongue and AAA's local edge-detection function is used to search for the best edge locally. AAA then assigns a confidence value to each of the control points on the equally-spaced 42-fan measurement grid, while smoothing the spline spatially within the frame. All splines from all /t/ and /k/ tokens were then averaged within target segment and within speaker and compared.

If there is evidence of convert contrast we would expect to see a difference in tongue shape for /t/ and /k/. To quantify this difference we used the method reported in Cleland et al., (2015). This uses the built-in statistical difference function in AAA where significance is tested radially from the virtual centre of the probe to the tongue surface, along each of the 42 fan-lines (Articulate Instruments, 2012). The threshold for reporting and estimating the size of the significant difference

between means is a minimum of six adjacent radii where the mean difference is significant at $p < .05$. These six adjacent radii are over a contiguous region of the tongue surface (approximately 2-3cm of surface), reflecting the fact that the adjacent parts of the tongue, and their distance from the fan-grid's origin (i.e. the centre of the probe) are not independent. This avoids reporting localised differences in tongue shape as clinically significant when they are unlikely to be so and is a conservative approach.

Results

Broad Phonetic Transcription

Table 3 shows the percentage of velars transcribed as correct for each child for all of the words in the probes. Six out of seven children perform similarly with no correct velars and all attempts transcribed as [t], demonstrating classic velar fronting in all word positions. The remaining child, 01F_UltraPhonix, produced 5% velars correct in broad transcription, with errors being transcribed as [t], but with two variants that were either centrally released or laterally released. She will be discussed in more detail in Study Two. Inter-rater reliability for 25% of the data was 95% (ranging from 83% to 100% agreement).

| Participant | Project | /k/ | |
|-------------|-------------|-----|--------------|
| | | PVC | Realisations |
| 01M | Ultrax | 0 | [t] |
| 05M | Ultrax | 0 | [t] |
| 06M | Ultrax | 0 | [t] |
| 07F | Ultrax | 0 | [t] |
| 01F | UltraPhonix | 5 | [t]*, [k] |
| 03F | UltraPhonix | 0 | [t] |
| 04M | UltraPhonix | 0 | [t] |

Table 3: Broad Phonetic Transcription Results. PVC: Percentage velars correct.
*Some attempts had clearly audible lateral release.

Ultrasound Analysis

Figure 2 shows the average /t/ (blue) and /k/ (red) tongue shapes for each child's attempts at the minimal pairs, with standard deviations represented with dotted lines. It can be seen that most of the children produce near-identical tongue-shapes for /t/ and /k/, with the exception of child

05M_Ultrax, where unexpectedly, /t/ appears have more dorsal raising. The seven children present with a wide variety of tongue-shapes, despite the consistent transcription as [t]. In part this is due to inter-speaker variability, including different vocal tract shapes, but it should also be noted that the rotation of the ultrasound images is not consistent across participants and this can lead to difficulty interpreting static images (without the context of the dynamics) across speakers and sessions. Statistical analysis using the in-built t-test function in AAA shows no significant difference between tongue shapes for /t/ and /k/ in any of the children, if the stringent criterion of difference in six adjacent fanlines is adhered to (Cleland et al., 2015). 04M_UltraPhonix did show a difference in the tongue root in three adjacent fanlines (lines 33-35, where fanlines are numbered 1 to 42 from tip to root, with an average distance between means of 2.87mm).

For 05M_Ultrax, the lack of a statistically significant difference in tongue shape between /t/ and /k/ is explained by a generally high standard deviation, representing extremely variable tongue shape during productions of /t/ and /k/. In short, contrary to expectations, the children in our study show no obvious evidence of covert contrast at an articulatory level in the mid-sagittal plane.

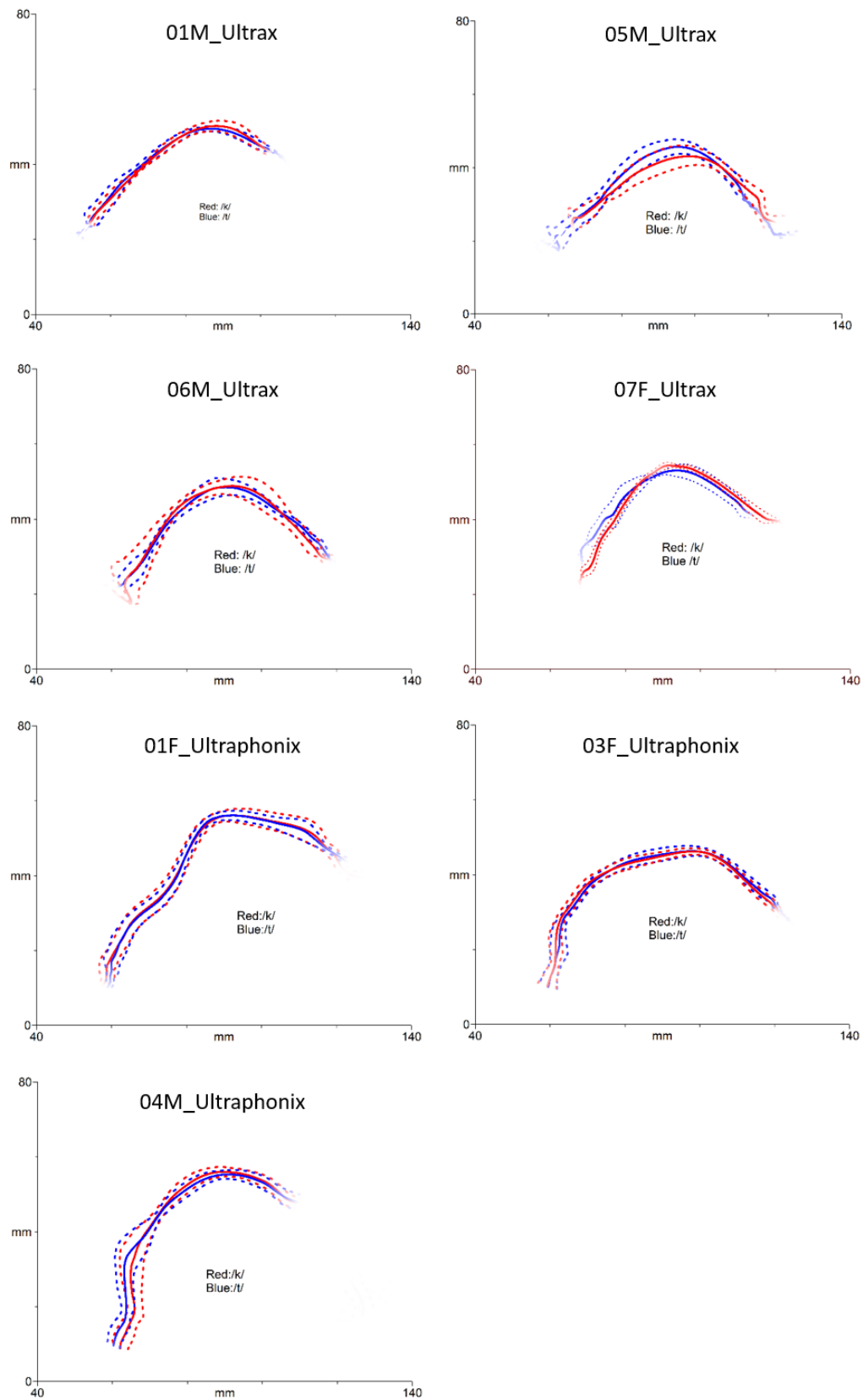


Figure 2: Average tongue splines for /k/ (red) and /t/ (blue) for each speaker. Dotted lines show standard deviations

Study Two: Single Case Study

Participant

Whilst lack of covert contrast at the articulatory level was in line with the auditory analysis in six of the children, for one child, 01F_Ultraphonix, “Rachel”, we were particularly surprised by lack of a contrast because some attempts at /k/ were noted as retroflexed [t] in the ultrasound images. This led the ultrasound clinician to suspect covert contrast based on her own subjective impression. Since previous research (Klein et al., 2013) has suggested that trained ultrasound clinicians might be reliable in online visual judgements of ultrasound images, further investigation of this particular child’s speech was undertaken to determine if covert contrast existed at the articulatory level in some phonologically patterned way that our previous analysis was insensitive to. Retroflexion was visually salient to the ultrasound clinician on raw ultrasound images, but not audible, nor was it immediately clear which, if any, linguistic targets a greater tendency of retroflexion was associated with.

The visual percept of a retroflex on the image includes artefacts, sometimes giving the impression of the tongue going beyond the hard palate. Though caused by reflections of ultrasound within the tongue, and the near-parallel orientation of tongue surface to ultrasound scanlines, these limitations of ultrasound are consistently present in retroflexion making these sounds easy to identify visually (Scobbie, Punnoose, & Khattab 2013).

The average tongue shapes for /t/ and /k/ at the burst (see fig 2, 01_UltraPhonix above) show no simple pattern of retroflex for /k/ vs. alveolar for /t/. In this case study we examine the client more extensively, to see whether covert contrast could be found by looking at the data for all productions of /t/ and /k/ (not just the minimal pairs), by examining other baseline sessions, and by looking qualitatively at the dynamics of the closure kinematics in the raw images.

01F_UltraPhonix, “Rachel”, was aged 8;8 at the time of the recording (session BL2). Rachel was referred to the project for “velar fronting” (which was confirmed, see above) but her mother

reported a complex history of poor attention, memory difficulties, and specific language impairment. She achieved a percentile rank of 50 on the Raven's Progressive Matrices (Raven, Raven & Court, 2003), suggesting normal cognitive ability, a standard score of 80 on the BPVS-3 (Dunn et al., 2009) and a standard core language score of 69 on the Clinical Evaluation of Language Fundamentals (CELF-4UK) (Semel, Wiig & Secord, 2006), consistent with the diagnosis of specific language impairment. On the Comprehensive Test of Phonological Processing (Wagner, Torgesen, & Rashotte, 1999) she achieved a "very poor" score on phonological awareness, a "poor" score on phonological memory and an "average" score on rapid symbolic naming. Orofacial examination identified a high-arched narrow palate, long narrow uvula, pointing of upper lip and saliva pooling at the corners of her lips.

Speech assessment with the DEAP (Dodd et al., 2002) showed that in addition to velar fronting, Rachel also presented with the developmental processes of gliding, cluster reduction and inconsistent deaffrication and the abnormal phonetic pattern of variable lateral release on oral stops. Probe assessment with a wordlist composed of 105 words containing 82 velars (some words contain no velars as they are minimal pairs, see above) showed velar fronting in all word positions with only 5% velars transcribed as [k] in broad phonetic transcription by the ultrasound clinician.

Ultrasound Analysis

We looked at all of the words containing word-initial or word-final /t/ or /k/ in the wordlist (see appendix for the words used here) in this session (BL2), and also examined two other baseline sessions from one week previous (BL1) and following (BL3) for qualitative confirmation, but can't report them fully here for reasons of space. This enabled us to analyse a much larger number of /t/ and /k/ from the word-list (n=34, n=53 respectively at each time point) and from sentences (n(t)=8, n(k)=16) since we were not constrained by using English minimal pairs. We also examined wordlist /d/ and /g/ in BL2 (WI n(d)=9, n(g)=13; WF n(d)=3, n(g)=8), but focus the results and discussion on

voiceless stops. Both series show the same pattern unless noted. Again, each stop was annotated at the burst (see above).

All recordings were inspected qualitatively to identify retroflex articulations by the second and third author using consensus agreement to identify retroflexion by looking at the dynamics of the stop articulation. We classified every token by hand as being either retroflex or not: clear retroflexion involves fairly strong retraction during closure and/or a curving of the tongue blade. Usually, the burst and maximal constriction showed only fairly subtle retraction or curving (Fig 3). Fig 4 exemplifies the dynamic aspects majority non-retroflexing situation. We used Fisher's exact test of contingencies to determine if our retroflexion categories patterned phonologically, for example with /t/ or with /k/ or by vowel environment.

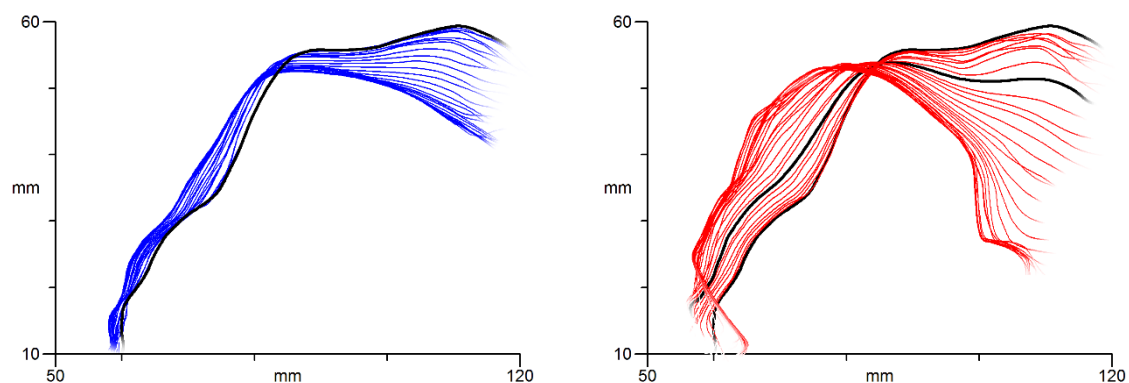


Figure 3. Retroflexing of /k/ in “coy”, /k/ = [t], dynamic sequences. Splines are ~8ms apart. Left: from pre-word stable shape to stop's maximal constriction (top black spline). Right: maximal constriction (top black spline) to the stable vowel target. The lower black spline is the shape at burst (around 63ms after the maximal constriction).

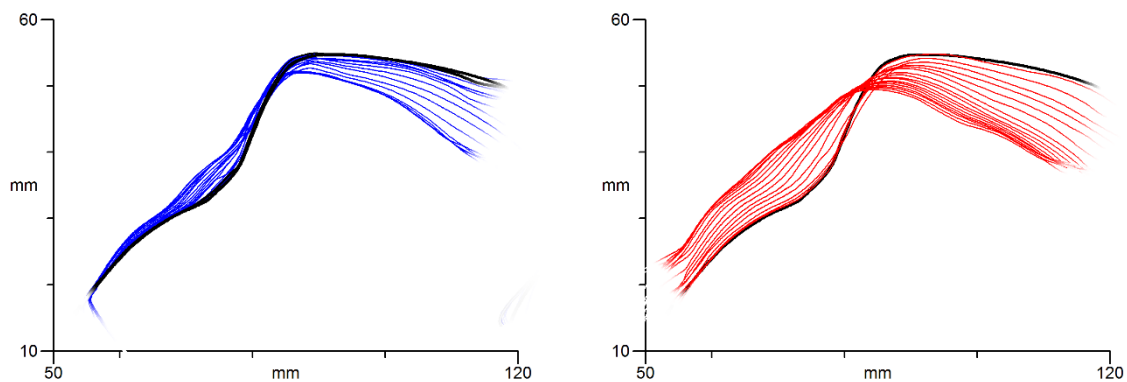


Figure 4. Non-retroflexing of /t/ in “tub”, /t/ = [t], dynamic sequences. Splines are ~8ms apart. Left: from pre-word stable shape to stop’s maximal constriction (top black spline). The acoustic burst was located 16ms before the maximal constriction, and is almost indistinguishable in shape. Right: the sequence from the maximal constriction (top black spline) to the stable vowel target.

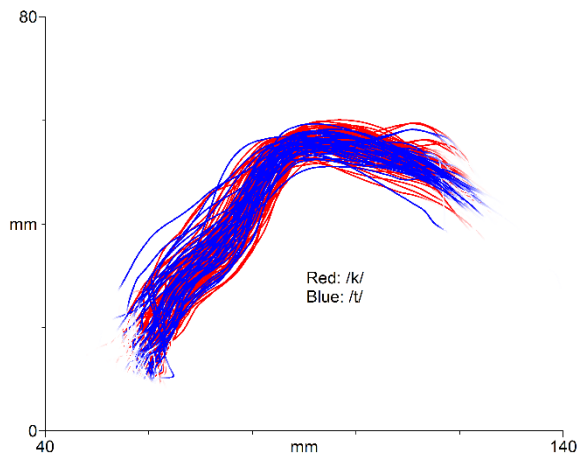


Figure 5: Tongue splines of all /k/s (red) and /t/s (blue) at stop burst

We hypothesised that /t/ vs. /k/ might be differentiated by retroflexion and/or that some other linguistic categories might be reflected in tongue shape differences: voicing, word position, and coarticulation with adjacent vowels. The diagram (Fig 5) of tongue surface splines at the acoustic burst, coloured by phoneme target, confirms that in both WI and WF position, some of the /t/ and /k/ show blade-raising and retroflexion during closure. We tested, again using t-tests, for differences in subsets of the data: words vs. sentences, and WI vs. WF, transcribed retroflex vs. others, voiced vs. voiceless. We also looked at the effect of coarticulation, examining the shape of /k/ and /t/ before high vowels vs. other vowels.

Results

We first confirmed from the larger, more varied dataset, that average /t/ vs. /k/ are not different when all data is pooled. Figure 6 shows the average tongue shapes for all WI and WF /t/ and /k/ and in keeping with the minimal pair data there was no significant difference between tongue curves.

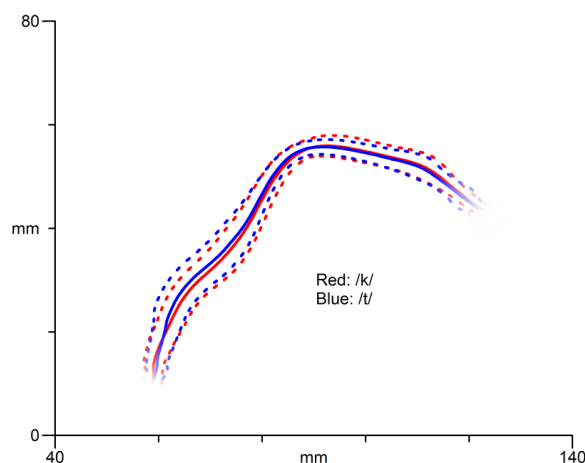


Figure 6: Average for all /t/ (blue) and /k/ (red) tongue splines

Comparing average plots of /t/ vs. /k/ in word-initial (WI) or word-final (WF) position shows no covert contrast in either, and neither is there any significant difference between WI minimal pairs versus WF pairs for either /t/ or /k/. Whether the stops appeared in sentences or words appeared also to be irrelevant. The auditory impression of lateral release, an aspect of variation that was sometimes present, did not appear to show up as a significant differentiator of tongue shape in the midsagittal plane, though careful placement of the probe in the coronal plane may have revealed this.

The average tongue shape at burst for the tokens coded as retroflex was significantly different from the others (Fig 7). Tongue shape also shows an anticipatory coarticulatory effect (Fig 8), in a CV context. In WI stops, a following high vowel appears to cause a more palatal, dorsally arched tongue shape.

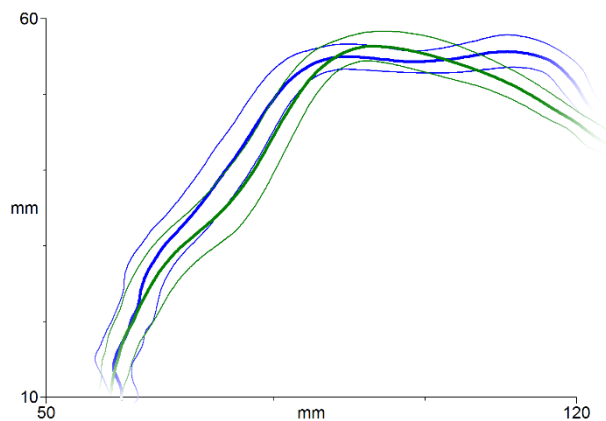


Figure 7: Averages for retroflex-like /k/ and /t/ (blue) and plain /k/ and /t/ (green)

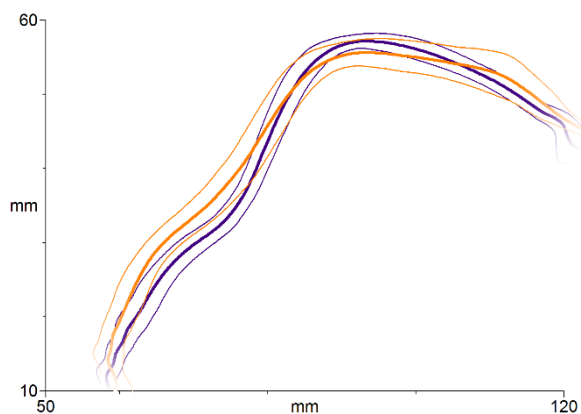


Figure 8: Averages for /k/ and /t/ before high vowels (purple) and elsewhere (orange)

Both these patterns seemed to be present not just in this baseline, but in the other two baselines too. We examined the distribution of transcribed retroflexes in relation to /k/ or /t/ target, and following high vowel or otherwise. The distribution of the retroflex type is shown in table 4, including also the BL1 and BL3 baseline sessions. These do not seem to pattern phonologically.

| BL1 | /k/ | /t/ | BL2 | /k/ | /T/ | BL3 | /k/ | /t/ |
|---------|-----|-----|-----|-----|-----|-----|-----|-----|
| retro | 3 | 0 | 5 | 4 | | 11 | 3 | |
| total | 26 | 11 | 33 | 19 | | 28 | 9 | |
| % retro | 12% | 0% | 15% | 21% | | 39% | 33% | |

Table 4: Distribution of retroflex articulation by target

| BL1 | high | other | BL2 | high | other | BL3 | high | other |
|---------|------|-------|-----|------|-------|-----|------|-------|
| retro | 2 | 1 | 0 | 9 | 1 | 13 | | |
| total | 15 | 22 | 20 | 32 | 14 | 25 | | |
| % retro | 13% | 5% | 0% | 28% | 7% | 52% | | |

Table 5: Distribution of retroflex type by vowel environment

In Table 5, from CV contexts, the vowel effect at stop burst seen above in Fig 8 can be seen in terms of the distribution of transcribed tokens. This is significant by a Fisher's Exact Test of contingencies ($p < .01$), confirming that the retroflexion is indeed not a function of /k/ vs. /t/, but of the vowel environment.

Though we found the same patterns in BL2 when it was possible to compare /d/ and /g/, or when pooling /t/ with /d/ and /k/ with /g/, we did notice a subtle difference in tongue surface due to phonological voicing. In WI position for /t/ vs. /d/ in words alone, and in pooled words and sentences, the root of /t/ was more retracted in the upper pharynx by about 2mm. For /k/ vs. /g/ pooled words and sentences were different, with the root of /k/ being more retracted by 1.5-2mm (but in words alone there was no statistical effect). However, if the WI stops from both places were pooled, there was no significant voicing effect. In WF position, a small voicing effect was noted in the blade area. The blade was slightly more raised in /k/ than in /g/, and for both places pooled, by over 3mm. (There were too few WF /d/ to analyse alveolars separately, and there was no significant tongue root difference).

Discussion

Study One: Group Study

This study sought to determine whether covert articulatory evidence of contrast could be found in children with persistent velar fronting. In comparing tongue shapes for attempts at /t/ and /k/ in

minimal pairs we found no evidence for covert contrast in any of the children in the mid-sagittal tongue shape at stop burst. Given that these children have particularly persistent velar fronting, and previous studies have suggested that covert contrast is highly prevalent (Munson et al., 2010), this was a surprising finding. Indeed, the average tongue splines for all the children show productions of /k/ to be very much what would be expected in typically developing children's productions of /t/. From this apparent lack of contrast it tempting to conclude that these children, unlike others reported previously in the EPG literature, present with a simple case of phonological delay.

However, it should be noted that covert contrast may have been observed with further analysis of the onset to, or offset from, the burst of the consonant, as is the case in previous EPG research, or that further recordings and analysis of coronal ultrasound may also have yielded different results. Dynamic analysis of closure phase is time consuming with ultrasound and unlikely to be usable in the speech therapy clinic. Likewise, there are no straightforward methods of analysing coronal ultrasound reported in the literature. Alternatively, it may still be possible to identify covert contrast in other aspects such as voice onset time using acoustic analysis or more holistically using a gradient perception experiment (see Munson et al., 2010), and we therefore cannot conclude that covert contrast, and therefore a phonetic cause of speech disorder, does not exist in these children.

Positive evidence for a phonetic-level disorder in our study comes from the observation that 5/7 children were unable to achieve a velar consonant in CV or in isolation, despite previous speech therapy targeting this very consonant. When this is the case Dodd (2013) suggests that an "articulation disorder" is the likely cause of impairment. These disorders are at the phonetic, or motor level, though they do not meet the diagnostic criteria for developmental verbal dyspraxia/childhood apraxia of speech.

Only one previous study has attempted to identify covert contrast using ultrasound. McAllister Byun et al. (2015) did find some evidence of covert contrast at the articulatory level.

However, this was in a single speaker of a much younger age and it is possible that he was in a period of natural acquisition of an overt contrast. This is unlikely to be the case in our participant group since these children all showed a long history of velar fronting across all word positions, and repeated probe baseline data (not reported here) showed no improvement in production of velars across time. A further intervention study of the four children from the Ultrax project has shown that these children did in fact quickly achieve an overt contrast between /t/ and /k/ using ultrasound visual biofeedback therapy, but these contrasts were achieved in a gradient manner with increasing dorsal differentiation towards a normal production by the end of the course of therapy (Cleland, Scobbie, Isles & Alexander, 2015).

The single case study, moreover, illustrates how ultrasound analysis is capable of detecting small and subtle differences in tongue shape arising from coarticulation, similar to EPG. This leads us to conclude that our general finding is not due to a lack of data, noise in the data, or problems with instrumental resolution (see below). Therefore, if not providing evidence of phonological neutralisation, the consistency of these seven cases demonstrates that a phonetic-level failure to encode place of articulation can lack any covert contrast in midsagittal tongue shape or location.

Study Two: Case Study

Further, and perhaps more convincing evidence of a motor-based impairment comes from our detailed case study of Rachel. In line with Klein et al.'s (2013) assertion that experienced ultrasound clinicians can identify ultrasound images by visual gestalt, Rachel was identified as a child likely to have unusual tongue shapes, namely retroflexes (the other children were thought not to present with unusual tongue shapes and this was confirmed by the analysis). While retroflexes were found in Rachel's speech these appear to be only one of a selection of tongue shapes that Rachel uses to realise both /k/ and /t/ (and /g/ and /d/). Lack of discernible phonologically patterning for these tongue shapes is interesting and points towards a motor-based speech impairment. In Rachel's case this seems to be a severe motor speech disorder, resulting in low intelligibility.

The subtle phonetic effects we show (a voicing difference and a coarticulatory difference) indicate that ultrasound is capable of picking up small, consistent differences in speech production, if they are present. We therefore take the lack of covert contrast at stop burst in the mid-sagittal plane (in Rachel and in the other children) to be a reliable finding, not just due to the use of ultrasound, rather than EPG.

As far as we are aware, retroflexion has not previously been described in the speech of children with persistent velar fronting, perhaps because EPG (the articulatory technique most used to identify covert contrasts and covert errors in children's speech) is not able to identify retroflexion. Rachel also demonstrated an "arched" tongue shape, characterised by dorsal raising (relative to typical development). We hypothesise that this is the same type of gesture described by Gibbon (1999) as an Undifferentiated Lingual Gesture (ULG). These gestures occur in the speech of children with persistent speech sound disorders and are taken by Gibbon (1999) to arise from a preservation of a developmental stage in which children lack differential control of the tongue tip/front and tongue body. ULGs are characterised by increased tongue-palate contact, which is easily identified with EPG, a technique which shows tongue-palate contact only. On the other hand, tongue-palate contact can only be inferred from ultrasound recordings because the palate is not imaged during the ultrasound recordings, though its location can be traced from recordings of swallows. Studies which employ simultaneous EPG and ultrasound would be useful in determining whether ultrasound can identify the same errors exemplified in EPG.

Moreover, the evidence for ULG in EPG usually comes from the entire closure phase of the lingual stop. This is particularly important if the tongue position changes during the closure phase such that the onset of closure is different from the release of closure, as illustrated in speaker "MB" by Gibbon (1990). In the group study we compared only tongue shape at burst (though qualitative dynamic information was used for Rachel), in part because identifying closure phases using ultrasound can only be done by hand and is then subject to difficulties with inter-analyst variability.

On the other hand, EPG only records contact, not close approximation, so has to infer a midsagittal arched tongue shape from peripheral patterns of contact. We conclude that that Rachel presents with ULG amongst other types of covert errors (i.e. retroflexion).

Clinical Use of Ultrasound for the Identification of Covertness

A secondary aim of this study was to investigate whether or not ultrasound was a viable tool for identifying covert contrasts and errors in the speech therapy clinic. By using a headset to stabilise the probe it was possible to average and overlay images in order to identify differences in tongue shapes between phonemic targets and unusual errors. Whilst for the purpose of this study we also compared the averaged tongue shapes statistically, it was possible to identify covert errors (or indeed lack of them) by visual inspection alone. This holds advantages over McAllister Byun et al. 's (2015) approach of extracting numerical information from ultrasound images and comparing these offline. However, in order for the approach presented here to be viable in the clinic, automatic and preferably real-time spline tracing would have to be employed since here this was achieved only semi-automatically. Development of robust, real-time, fully automatic contour tracking which could be employed in a clinical tool for comparing and classifying tongue shapes automatically is ongoing in various labs (Xu et al., 2015; Fabre et al., 2015) and results indicate that a practical method is likely in the near future. Nevertheless, raw ultrasound images themselves do show some errors very clearly, especially retroflexion. Importantly, ultrasound shows promise as a diagnostic tool for motor-based speech disorders, which works in tandem with ultrasound visual biofeedback for motor-based intervention.

Conclusion

In summary, we found no evidence for covert articulatory contrast for seven school-aged children with persistent velar fronting in mid-sagittal tongue-shape at the stop burst. Future research could expand the search for covert contrast in ultrasound data through quantitative dynamic analysis of

the entire stop-closure phase, augmented with a perception experiment designed to investigate the gradient nature of stop continua, such as the visual analogue scale used by Munson et al. (2010). The nature of these children's speech sound disorder remains unclear, with both phonological and phonetic impairment remaining as candidate causes.

Our single case study, Rachel, also showed no evidence of a covert phonemic contrast of stop place at the articulatory level, in the midsagittal tongue shape at stop release. However she clearly shows a "covert error" of retroflexion which as far as we are aware has not been reported in acquisition of velars in typically developing children, though it is conceivable that some of the reported acoustic difference in young children's neutralised productions of /t/ and /k/ are due to tongue shapes not attested in typical adults. This hypothesis is difficult to test without articulatory information from young children less than three years old which is experimentally difficult to acquire. We also showed Rachel has small, consistent reflexes of stop voicing and that both velar and alveolar stops tend not to be retroflexed before a following high vowel. For Rachel, the presence of a covert error in her speech with a lack of phonological patterning for target stop place suggests a motor-based speech impairment in line with previous research by Gibbon (1990) on undifferentiated lingual gestures in children with persistent speech sound disorders. Despite the apparent absolute neutralisation of the phonological place contrast which might suggest phonological therapy, the diagnostic value of these covert phonetic errors is that they suggest the selection of therapy approaches which capitalise on motor learning.

Acknowledgments

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Declarations of Interest

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Appendix: Wordlist for Study 2

| Word Initial /k/ | Minimal pair |
|------------------|--------------|
| keep | team |
| cape | tape |
| ken | ten |
| cab | tab |
| cop | top |
| core | tore |
| cool | tool |
| cub | tub |
| kip | tip |
| Kai | tie |
| couch | |
| coy | toy |
| cube | tube |

| Word Final /k/ | Minimal Pair |
|----------------|--------------|
| meek | meet |
| make | mate |
| peck | pet |
| pack | pat |
| mock | pot |
| boak | boat |
| took | toot |
| muck | mut |
| lick | lit |
| Mike | might |

Sentences

Kenny drank a tiny tin of coke

My Granny Maggie got a golden gown

Ken likes scones with cream and apricot jam

Kevin got a cab to the coast

Happy Karen is making a cake